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ELIMINATION OF WATER AND MINERAL NUTRITION AS LIMITING FACTORS IN A YOUNG SCOTS PINE STAND.
I. EXPERIMENTAL DESIGN AND SOME PRELIMINARY RESULTS

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Contents

Abstract.. 3
1. Introduction.. 3
2. Site description...................................... 5
3. Methods... 7
3.1 Treatments... 7
3.1.1 Control plots...................................... 9
3.1.2 Irrigation plots................................... 9
3.1.3 Fertilization plots................................. 10
3.1.4 Irrigation plus fertilization plots................ 12
3.2 Irrigation equipment................................. 14
3.2.1 Construction....................................... 14
3.2.2 Function... 17
3.3 Sampling... 17
3.4 Chemical analysis.................................... 19
4. Results... 21
5. Discussion.. 29
6. References.. 36

ELIMINATION OF WATER AND MINERAL NUTRITION AS LIMITING FACTORS IN A YOUNG SCOTS PINE STAND. I. EXPERIMENTAL DESIGN AND SOME PRELIMINARY RESULTS

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Abstract

An irrigation system built up on an experimental site in mid-Sweden is described. The main species on the site is Scots pine about twenty years old grown on a deep deposit of outwash sand. The treatments are: irrigation every day during the growing season, fertilization with solid fertilizer once a year, and daily irrigation plus fertilization five days a week during the growing season. Needle samples are taken and analysed for their content of N, K, P, Ca and Mg. Soil water status and percolation of mineral nutrients are measured and discussed. The variation in mineral nutrient content at different ages of needles is discussed on dry weight basis for the years 1974, 1975 and 1976, and the contents of K, P, Ca and Mg are compared with the nitrogen content.

1. Introduction

Mineral nutrients, and especially nitrogen, are generally growth-limiting factors in Swedish forests (cf. Tamm 1968, Tamm et al. 1974, Holmen et al. 1976). It is very likely that water also generally limits growth, at least during parts of the vegetation period. When nitrogen availability increases, e.g. after fertilization, other nutrients - as well as water - tend to be the growth-determining factors. Such effects of one-sided nitrogen fertilization mean that the efficiency of the nitrogen added may be limited or even insignificant. Laboratory experiments show that the balance between the nutrients is essential for the physiological status and growth ability of various plant species (Ingestad 1970, 1971, 1973a, 1973b). The balance seems to be even more important than the absolute level within a rather wide range. Such relations are probably of significant importance for other growth factors, such as, for instance, the water balance. In conifers the connections between nutrient status, water balance, photosynthesis, and growth are further complicated and obscured by dynamic changes in the amounts and location in the tree crown of needles of various age. Furthermore, conifers seem to have mechanisms for redistribution of nutrients and water within the plant, which probably implies a good economy with nutrients once taken up and adaptation of leaf and root amounts to the site conditions. Such adaptation processes may occur slowly over several years. It is well known that the needle's life-span is strongly influenced by the nitrogen status (Romell and Malmström 1945) and the amount of needle formed increases strongly after fertilization (Miller and Miller 1976, Tamm 1974, 1976). An increased photosynthesis activity per unit needle is also to be expected when nutrient and water availability is improved. However, adaptation reactions and efficiency of nutrients and water on stand production are understood only to a limited extent. This investigation is a part of the Swedish Coniferous Forest Project and the aim is to study the relations between mineral nutrient status, water balance and photosynthesis, and their role in stand growth and development. By fertilization and irrigation the growth-limiting effect of mineral nutrition and water availability are made, as far as possible, negligible in a young stand of pine (*Pinus silvestris* L.). Treatments with conventional fertilizers (cf. Tamm et al. 1974, Holmen et al. 1976) and irrigation alone are carried out on parallel plots for comparison.

When fertilizing to increase growth, it is important that the treatment as such does not affect growth. Thus, to avoid high concentrations of the nutrient salts, which may be deleterious (Ingestad 1977a) and to keep the internal nutrient status of the trees as constant as possible (Ingestad 1977b), the additions of nutrients are made five days a week during the season and according to a dosage scheme as close as possible to the requirement and uptake curves. To avoid false and growth-restricting nutrient proportions, all nutrients are added throughout, including the micro nutrients, according to the optimum proportions of forest tree species in Sweden (Ingestad 1971, 1977a). As a result of these measures, no single nutrient may be regarded as specifically limiting growth. To be able to analyse production effects and translocation of the nutrients, needles of various age and position in the crown are sampled for chemical analysis and various measurements. Within the Swedish Coniferous Forest Project further measurements are carried out by other groups (cf. Flower-Ellis et al. 1976, Hellkvist et al. 1975, 1977).

The present paper only gives some background material and the aim here is restricted to a description of the equipment and its function. Examples of collected data and tendencies found are given. The long-term character of the experiment and the data required from other groups means that conclusions at present can only be drawn to a limited extent.

2. Site description

The experimental site is situated in the youngest stand, Ih II, within the experimental area Ivantjärnsheden at lat. 60° 49´N and long. 16° 30´E in the middle of Sweden. Ivantjärnsheden is a sand plain about 185 m above sea level, i.e. just below the highest post-glacial shore line, which is about 210 m in this area (Bråkenhielm 1974). The soil consists of a very deep layer of sand, at least 15-20 m. In Ih II the top layer is coarse sand, which was probably deposited when the ice melted away from the area. On one side of the site a small river, Jädraån, has eroded a 20-25 m deep gully with a very steep slope from the heath. Ih II is situated between 150 to 500 m east of the river and it can be assumed that water from the site percolates into the river through the deep layers of sand.

The yearly precipitation is about 600 mm and the humidity is normal for Sweden (Tamm 1959, Ångström 1953). Figure 1 shows temperature and precipitation monthly for the period 1931-1960 for the meteorological station Åmotsbruk, 15 km north of Ivantjärnsheden (Axelsson 1976).

The soil profile is a podsol with a rather thin F/H-layer of only a few cm thickness and a A_2-layer of about the same thickness. At about 30 cm depth there is, in some patches, a weakly developed hardpan.

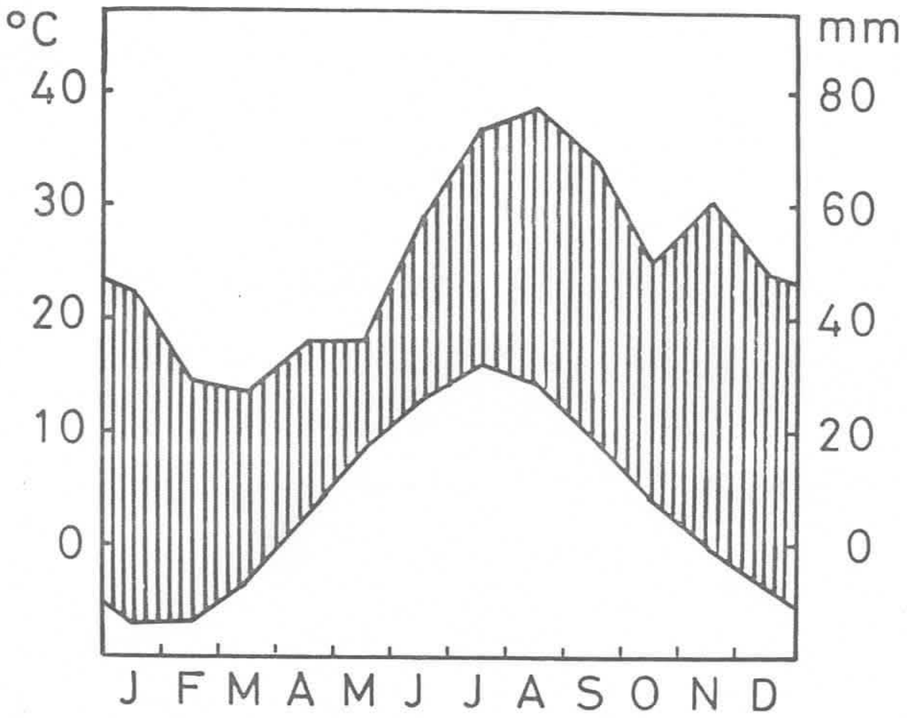

Fig. 1. Climatic diagram (cf. Walter and Lieth 1961-1967) for Åmotsbruk situated 15 km north of Ivantjärnsheden. Mean monthly temperatures (lower curve) and mean monthly precipitation (upper curve). Both curves are calculated as average for the period 1931-1960. Mean annual temperature 3.8°C and mean annual precipitation 607 mm.

The vegetation of Ih II is a *Cladonia-Pinetum(boreale)* (Cajander 1921, Kielland-Lund 1967) or according to Arnborg (1953) a "very dry to dry dwarf shrub type" (Bråkenhielm 1974). The dominant plant in the field layer before the experiment started was *Calluna vulgaris* growing in more or less circular clones, mostly originating in scarified patches. Persson (1975) reported on the dry matter production of field and bottom layer vegetation at Ivantjärnsheden and stratified the Ih II site into *Calluna* and non-*Calluna* strata. The non-*Calluna* stratum was largely occupied by different *Cladonia*-species. *Vaccinium vitis-idaea* was also fairly abundant all over the site (Persson 1975). The previous stand at Ih II was an almost pure stand of rather old pines, which was harvested in 1957. Seed-trees left at that time were felled in 1962. In autumn 1973 before the irrigation and fertilization experiment had started, the stand was cleaned and space-regulated by removing the tallest and most widely branched trees. A few young birches were also removed. All trees cut down during this cleaning were taken away from the site. Despite these levelling treatments, the stand remained uneven. At an early stage of the Coniferous Forest Project, the site had been divided into plots of 10 x 10 m and before the experiment was laid out all trees in each of these plots were counted. For the purpose of this experiment 20 plots of 30 x 30 m or 30 x 40 m were laid out within the mentioned 10 x 10 m pattern on the site in such a way that the plots were as even as possible with regard to the numbers of trees (see section 3.1). After cleaning and levelling, there were about 1100 trees per ha which were taller than 1.0 m and with an average height of about 2.1 m (Flower-Ellis et al. 1976, Table 4).

3. Methods

3.1 Treatments

This experiment aimed at improving the supply of water and mineral nutrition in the soil, thus eliminating the growth restrictions exerted by these limiting factors on the site. In addition to the control plots without any treatment there were three treatments in the experiment: irrigation, fertilization and irrigation plus fertilization (Table 1).

Table 1. The size and treatment of the different plots. 0: control, no treatment, I: irrigation, F: fertilization, IF: irrigation plus fertilization with liquid fertilizer.

Block no	Plot no	Size m^2	Treatment 0	I	F	IF
1	1	1 200			X	
	2	1 200	X			
	3	1 200		X		
	4	1 200				X
2	5	1 200			X	
	6	1 200		X		
	7	1 200				X
	8	1 200	X			
3	9	900	X			
	10	900			X	
	11	900		X		
	12	900				X
4	13	900				X
	14	900			X	
	15	900	X			
	16	900		X		
5	17	1 200		X		
	18	1 200	X			
	19	1 200			X	
	20	1 200				X

The experiment was designed as a block experiment with five blocks of four randomly laid out plots. Considering the conditions in the ground the five blocks are not equal. Block one has a better soil water status than block three. The height and development of the trees were better in block one than in any of the others. The size of the plots was originally 30 m x 30 m but an area of 10 m x 30 m was added to the plots in three blocks (Figures 2 and 3). Within the original plots an area of 20 m x 20 m is used as a net plot with a margin of 5 m.

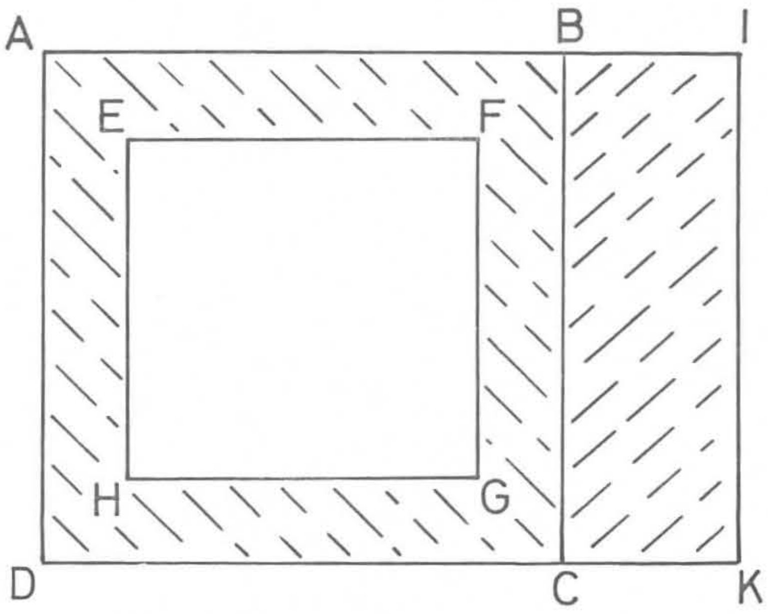

Figure 2. Experimental plot. Root isolation is performed along the sides ABIKCDA if the plot is surrounded by plots with other treatments. ABCDA: original plot, 30 x 30 m^2; EFGHE: net plot, 20 x 20 m^2; BIKCB: area for destructive sampling, 10 x 30 m^2.

The whole plot, 30 m x 30 m or 30 m x 40 m respectively, was treated (irrigated or fertilized). The plots were isolated from each other by sheets of aluminium forced 33 cm into the soil in order to prevent the roots from one plot growing into the neighbouring plot. The 20 m x 20 m part of the plots is reserved for sampling of needles for analyses of mineral nutrition content etc. (see section 3.3) as well as different measurements of growth, water potential of the trees and so on. All other types of activities that may influence the growth of the trees are forbidden in this area. Samples for other experiments may be taken in the margin and more destructive types of samples may be taken in the additional area of 10 m x 30 m.

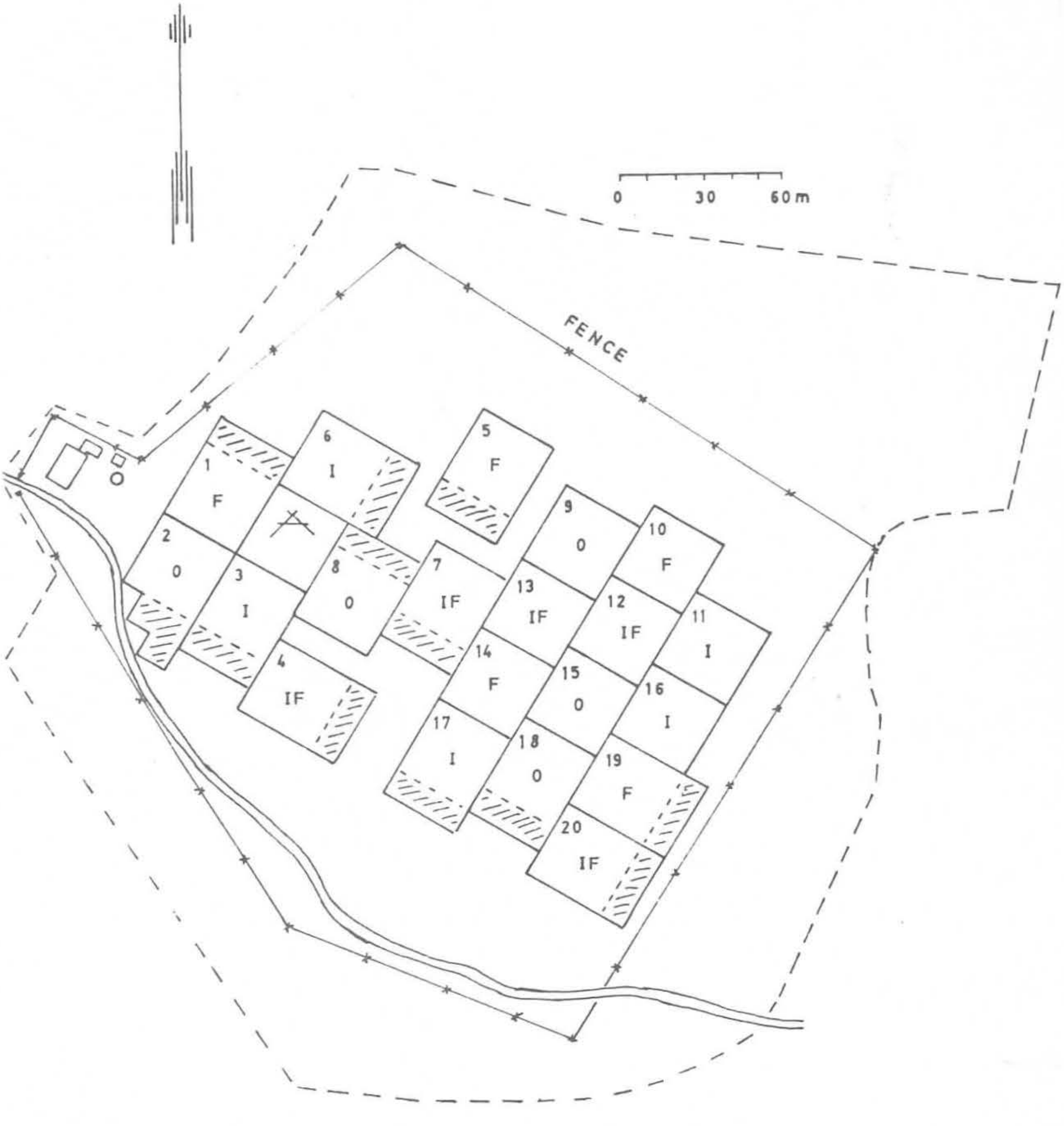

Figure 3. Map of the experimental site Ih II. The plots are numbered from 1 to 20; 0: control, I: irrigation, F: fertilization and IF: irrigation plus fertilization. Between plots numbers 3 and 6 there is a meteorological mast. In the west there is the field laboratory with the irrigation equipment and the ponds (□) and the drilled well (○).

3.1.1 Control plots, 0

In these plots no treatment at all has been performed except the cleaning of the stand as described in section 2.

3.1.2 Irrigation plots, I

The water is distributed to the plots by irrigation equipment (see section 3.2). The water status in the ground is studied by measurements of water potential by tensiometers. During the summer the mean evapotranspiration was calculated to be 3 l/m^2 per day (= a precipitation of 3 mm) and the standard amount of irrigated water was therefore of the same amount. During long periods of dry weather up to 4 l/m^2 per day can be supplied. On the other hand, the handling of the liquid fertilizer does not allow less than 2 l/m^2 per day to be irrigated (see section 3.1.4).

The plots were irrigated five days a week in 1974 and every day during 1975 and 1976. Irrigation starts in mid-May (Table 2). In the first year of the treatments (1974) irrigation did not start until July 12 owing to the incompletion of the irrigation equipment. Figure 4 shows the amount of precipitation and irrigation during the years 1974, 1975 and 1976. (See next page)

3.1.3 Fertilization plots, F

Fertilization with solid fertilizer is done once a year (Table 2). The treatment is different from year to year over a period of three years (Table 3). This treatment is similar to the treatment that gave high production in other field experiments not far from Ivantjärnsheden and on similar soil (cf. Tamm et al. 1974).

Three solid fertilizers are used: Ammonium nitrate with 26% N, triple superphosphate with a total content of 19.5% P and potassium sulphate with 41.5% K.

Table 2. The regime of irrigation and fertilization during the summer 1974-76 and the total precipitation during the same period.

Year	Irrigation		Precipitation	Fertilization					
				Liquid Fertilizer		Solid Fertilizer			
					1)		g element/m^2		
	from to	mm	mm	from to	g N/m^2	date	N	P	K
1974	12.7-19.9	100	100	12.7- 9.8	7	15-16.7	8	3	6
1975	23.5-12.9	300	180	23.5-22.8	10	6.6	8	-	-
1976	20.5-18.9	300	250	20.5-20.8	15	3-4.6	8	-	-

1) other essential elements given in fixed proportion to N, see Table 5.

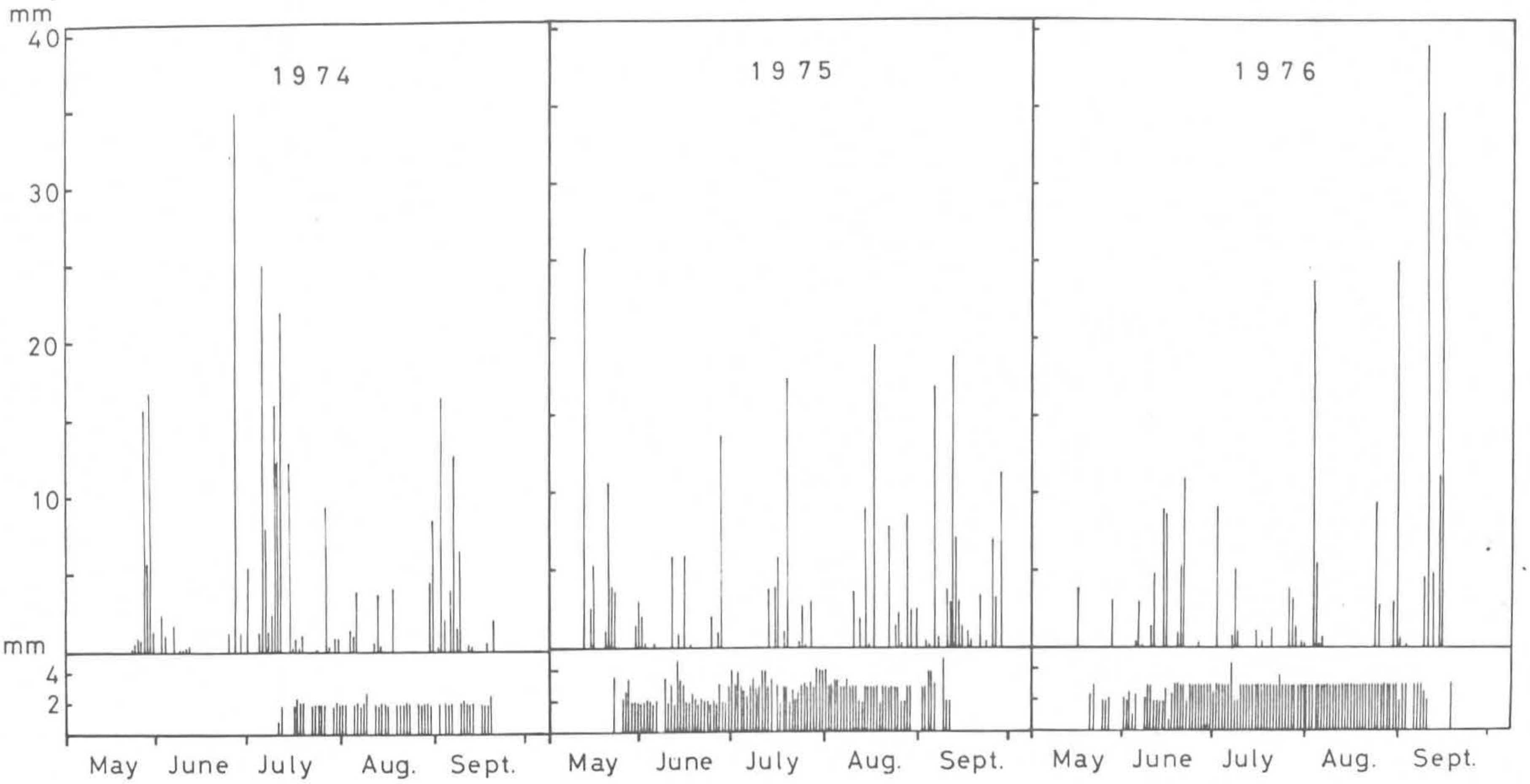

Figure 4. Precipitation (above) and irrigation (below) during 1974-1975 and 1976.

Table 3. Treatment with solid and liquid fertilizer. The elements N, P and K in g/m^2.

Year		Liquid fertilizer			Solid fertilizer		
		N	P	K	N	P	K
1974,	I	7.0	0.9	4.6	8.0	3.0	6.0
1975,	II	10.0	1.3	6.5	8.0	-	-
1976,	III	15.0	2.0	9.8	8.0	-	-
1977,	I	1)	1)	1)	8.0	3.0	6.0

1) The amount of liquid fertilizer that will be given to the plots has not yet been decided.

3.1.4 Irrigation plus fertilization, IF

The liquid fertilizer is distributed to the plots with the same equipment as the water. The treatment starts at the same time as the irrigation (Tables 2, 4 and Figure 5). The mineral nutrient requirement for maximum production was calculated from the beginning to be 10 g N per m^2 and year. All other essential elements are given in proportion to N (Table 5) (Ingestad 1967, 1971, 1977a). The pine needles are continuously analysed for content of mineral nutrients and the results indicate whether the treatment is near optimum or below. The fertilizer is given on five days a week and only irrigation is supplied on Saturdays and Sundays.

Table 4. The weekly regime of fertilizer with liquid fertilizer. The amount of fertilizer put as g N/m^2 and the other essential elements in fixed proportion to N, see Table 5.

Week no	1974	1975	1976
21			0.6
22		0.2	0.9
23		0.4	1.5
24		0.8	1.5
25		1.0	1.5
26		1.2	1.5
27		1.5	1.5
28	1.0	1.5	1.5
29	1.5	1.2	1.5
30	1.5	0.8	1.0
31	1.5	0.6	0.8
32	1.5	0.4	0.6
33		0.2	0.4
34		0.2	0.2

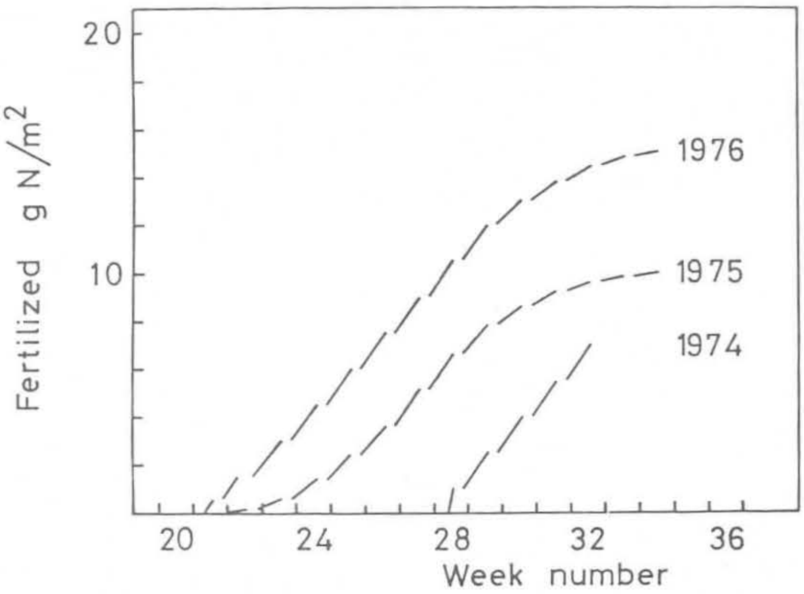

Figure 5. Fertilization regime for IF plots 1974, 1975 and 1976. All other elements are given in fixed proportion to N, see Table 5.

Table 5. The mixture of the liquid fertilizer. The N content is put to 100 units and the other elements in proportion to N (Ingestad 1967).

Element	Proportions		Element	Proportions	
	by weight	by molarity		by weight	by molarity
N	100	100	Fe	0.70	0.18
K	65	23	Mn	0.40	0.10
P	13	5.9	B	0.20	0.26
			Cu	0.030	0.0067
Ca	7	2.5	Zn	0.030	0.0064
Mg	8.5	4.9	Mo	0.007	0.0010
S	9	3.9	Na	0.0034	0.0020
			Cl	0.033	0.013

3.2 Irrigation equipment

3.2.1 Construction

Irrigation and fertilization with liquid fertilizer is achieved with equipment built as two separate systems (Figure 6). The water is taken from a 35 m well on the site which gives about 3500 l per hour. The water is stored in two ponds, one for the irrigation water (45 m^2) and one for the liquid fertilizer (7 m^3). The ponds are made of concrete and are roofed to prevent dust and needles from polluting the water. The temperature of the water varies from +5 to +10°C.

All the tubes are made of black polyethylene. The diameter of tube T1 is 63/51 mm (outer/internal diameter), of T2 50/40 mm (Figure 6) and of T3 25/20 mm (Figure 7). The flow rate is about 300-360 l/min depending on the size of the plots. Water is distributed from the pond to the plots by a centrifugal pump, PI, (Caprari, series "MEC-A"). The distribution pressure is 6-7 kg/cm^2. The flow is measured by a flow meter and for each 10 l an electric signal is given to the electric panel and the amount of irrigated water is registered (see section 3.2.2). On the plots the water is distributed as small droplets by sprinklers (Rian Bird, model A-771, Low angle spray head) (Figure 7). The sprinklers are mounted 50 cm above the ground and the water is spread in a circle with a diameter of about 5.5 m. The water distribution is not even due to the pattern of the sprinklers and to the trees on the plots.

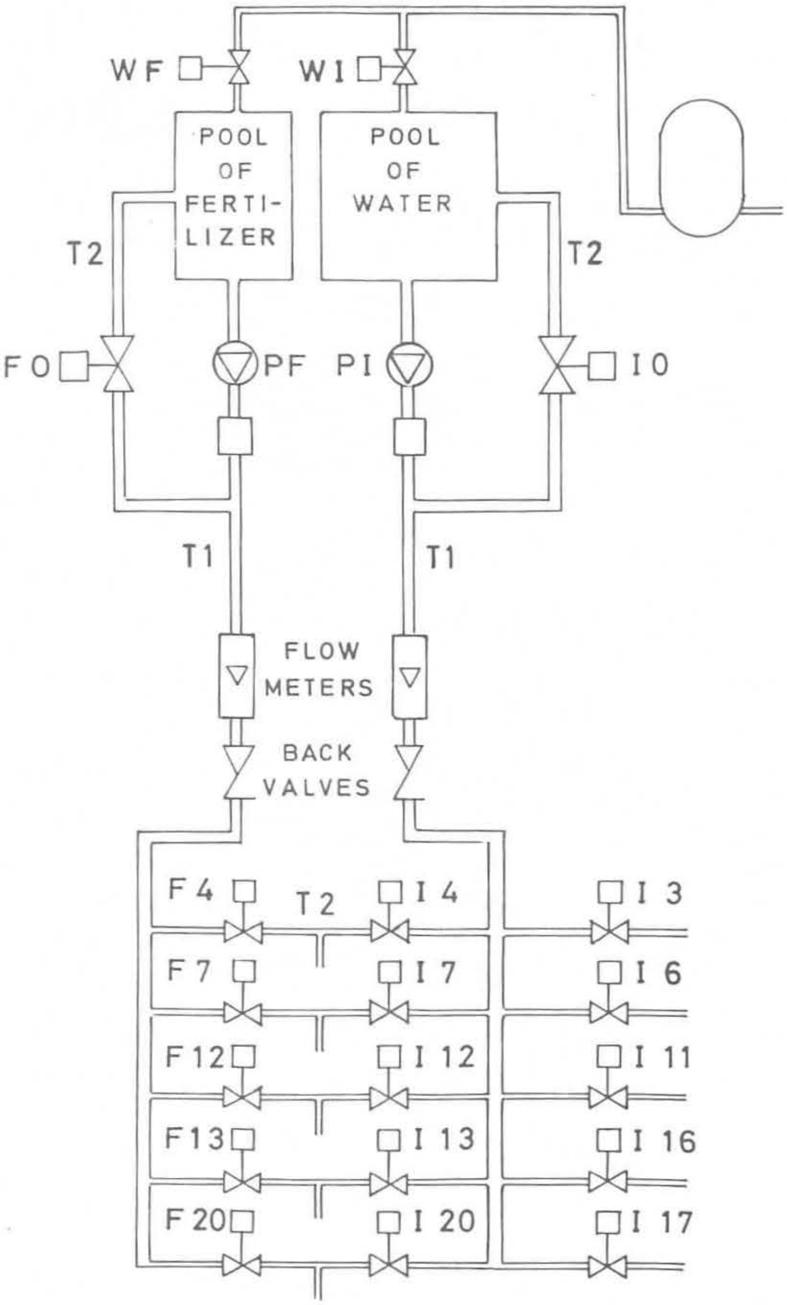

Figure 6. Equipment for irrigation and fertilization with liquid fertilizer. PI and PF centrifugal pumps. WF and WI solenoid valves for refilling the ponds with water. FO and IO solenoid valves for recirculation of liquid. F4-F20 and I3-I20 solenoid valves for distribution of liquid to the plots. T1 and T2 tubes of black polyethylene.

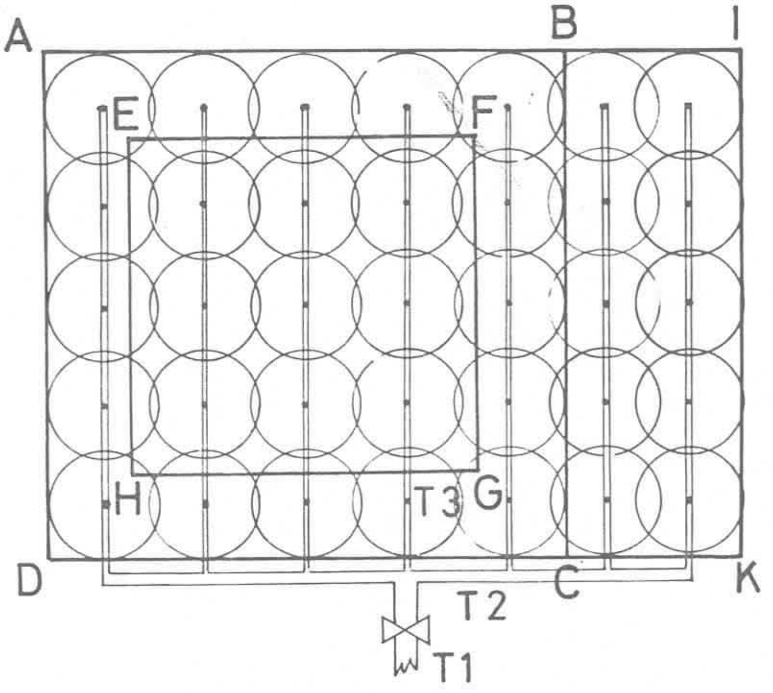

Figure 7. The pattern of sprinklers on the treated plots. ABCDA: original plot, EFGHE: net plot, BIKCB: area for destructive sampling.

The distribution of liquid fertilizer is by means of an identical system but with a pond of 7 m^3. The fertilizer is spread on the plots by the same sprinkler system as the water.

The electric solenoid valves are for the valves WF, WI, FO and IO BUCKNER 1.5", Type 113 GE and for F4-20, I4-20 and 13-17 BUCKNER 2", ype 113 GE (Figure 6). The F4-20 valve was replaced in 1976 with a BÜRKERT 2/2, Type 181 the function of which has proved to be more convenient for this purpose. All the solenoid valves are served by 24 V AC.

The electric panel controlling the irrigation and fertilization can be set either manually or automatically. The daily amount of water and fertilizer is programmed into the apparatus. During the treatment the flow of liquid is recorded for every plot. If a fault arises the treatment is stopped and an alarm lamp is switched on. The program can be started either manually or by a clock.

3.2.2 Function

The irrigation is by means of the irrigation system which distributes the programmed amount of water to the plots. The liquid fertilizer is distributed by the fertilizer system. The amount of fertilizer is always given together with one l/m^2 of water and is followed by irrigation of at least one l/m^2. This irrigation washes the fertilizer from needles and plants down into the soil. The amount of fertilizer plus water is programmed to the same amount as irrigation water per m^2 and treatment. The daily amount of concentrated fertilizer is poured into the fertilizer pond. The program is started and after that it performs automatically. The two pumps, PF and PI, start and the solenoid valves F0 and I0 open. By opening this by-pass the water and fertilizer are pumped back into the ponds and prevent too high a pressure being built up in the systems and damaging the tubes. It also serves to thoroughly mix the concentrated fertilizer with the water in the fertilizer pool. After some minutes the programmed treatment of the first plot starts when valve F0 (or I0 respectively) closes and the valve on this plot opens. The treatment finishes by the closing of the valve on the plot and the reopening of valve F0 (I0). The treatment of the next plot then starts. After the closing of one solenoid valve and the opening of another there is a delay of five to ten seconds to make sure that the first valve has been completely closed. After treatment of all plots the pumps stop and the valves WF and WI open to refill the ponds with water.

3.3 Sampling

In order to follow the effect of the treatments on the content of mineral nutrients in the needles, samples have been collected about twenty times each year during the 1974 to 1976 period (Table 6). From each net plot (Figure 2) 12 trees were selected for sampling. The needles were taken from the main axis. The current needles are called C, one-year-old needles C+1 and so on. The changes from C to C+1 (C+1 to C+2 etc.) are set to January 1, partly for modelling purposes, but also partly because it is hard to decide when the growing season starts. It is also difficult to decide when the growing bud can be regarded as a shoot. Moreover, these events occur on different dates in different years. For further explanations of the terms used here see Flower-Ellis et al. 1976.

Table 6. The dates when needle samples are taken during 1974, 1975 and 1976.

Sampling nr	1974									1975									1976								
	Week nr	Date	Sampling from block nr					Whorl nr		Week nr	Date	Sampling from block nr					Whorl nr		Week nr	Date	Sampling from block nr					Whorl nr	
			1	2	3	4	5	3	6			1	2	3	4	5	3	6			1	2	3	4	5	3	6
1	18	29 April	x	x				x	x	10	6 March	x	x				x	x	10	4 March	x	x				x	x
2	19	8/9 May	x	x	x	x	x	x	x	14	3 April		x	x			x	x	14	1 April		x	x			x	
3	21	21		x	x			x	x	17	24	x	x	x	x	x	x	x	17	22			x	x		x	
4	22	31			x	x		x	x	19	7 May			x	x		x		19	6 May				x	x	x	
5	23	7 June				x	x	x	x	21	22				x	x	x		21	20	x				x	x	
6	24	14	x				x	x	x	22	29	x				x	x		22	26	x	x				x	
7	26	25	x	x				x	x	23	5 June	x	x				x		23	3 June		x	x			x	x
8	27	5 July		x	x			x	x	24	12		x	x			x	x	24	10			x	x		x	
9	28	12			x	x		x	x	25	19			x	x		x		25	17				x	x	x	
10	29	19				x	x	x	x	26	26				x	x	x		26	24	x				x	x	
11	30	26	x				x	x	x	27	3 July	x				x	x		27	1 July	x	x				x	
12	31	2 Aug.	x	x				x	x	28	10	x	x				x		28	8		x	x			x	
13	32	9		x	x			x	x	29	17		x	x			x	x	29	15			x	x		x	
14	33	14			x	x		x	x	30	24			x	x		x		30	22				x	x	x	
15	34	23				x	x	x	x	31	31				x	x	x		31	29	x				x	x	
16	35	30	x				x	x	x	32	7 Aug.	x				x	x		32	5 Aug.	x	x				x	
17	36	6 Sept.	x	x				x	x	33	14	x	x				x		33	12		x	x			x	x
18	37	11		x	x			x	x	34	21		x	x			x		34	19			x	x		x	
19	38	19			x	x		x	x	36	4 Sept.			x	x		x		36	2 Sept.				x	x	x	
20	39	26/27	x	x	x	x	x	x	x	38	18	x	x	x	x	x	x	x	38	16	x	x	x	x	x	x	x
21	42	17 Oct.				x	x	x	x	43	23 Oct.	x				x	x		43	21 Oct.	x				x	x	
22	48	28 Nov.	x				x	x	x	50	11 Dec.	x	x				x		50	9 Dec.	x	x				x	
	1975									1976																	
23	10	6 March	x	x				4	7	10	4 March	x	x				4	7									
	First C-needles 12 July									First C-needles 26 June									First C-needles 1 July								

The sample branches have been taken from the third whorl. During 1974 and on some occasions during 1975 and 1976 samples were also taken from the sixth whorl (Table 6). The branches were taken from the south side of the trees. Whorls were numbered from the top of the trees downwards. During 1974, 12 needles were collected from each year-class and from two branches per whorl and tree on each occasion. In order to reduce the sampled amount of needles per shoot and thus minimize the disturbance the removal might cause on the growth of the trees, the sampling was changed in 1975 and 1976 to six needles per year-class and to three branches per whorl and tree. Although these quantities of needles are small it was not possible to sample all trees chosen on all sampling occasions during the year. Therefore samples were taken from two blocks on each occasion. Samples were taken from all blocks on one or two occasions per year for simultaneous comparison between blocks (Table 6). When the needles are collected, they are divided into four different sub-samples. During 1974 half the amount of needles was used for analysis of the mineral nutrient content, while the other half was divided equally between three other sub-projects within the Coniferous Forest Project. In 1975 and 1976 only one-third was used by these three sub-projects. These samples were analysed for the chlorophyll content of the needles, carbohydrate analysis and measurements of growth and dry weight changes during the year.

During the collecting time, normally from seven to twelve o'clock the needles are stored in small plastic tubes inserted in a well insulated box with small holes through which the needles are put into the tubes. The needles used for analysis of mineral nutrients are transferred to small paper bags and dried for 45-60 hours at 70°C. The dry weight is calculated and the needles are counted.

3.4 Chemical analysis

The needles were analysed for their content of nitrogen, potassium, phosphorus, calcium and magnesium on dry weight basis.

Until the middle of 1975 total-N was determined titrimetrically by a micro-Kjeldahl method. The vacuum-oven dried sample was digested by boiling for about three hours in sulphuric acid to which was added salicylic acid and sodium sulphate. Distillation was done by a modified Parnas-apparatus. The ammonia was collected in 0.01 M hydrochloric acid and the excess acid was titrated with sodium hydroxide and with an indicator consisting of a mixture of methyl red and methylene blue.

From mid-1975 the nitrogen analysis was changed from titrimetric to colorimetric determination of ammonia. Digestion of the samples was almost the same as earlier. The samples were boiled in sulphuric acid to which was added hydrogen peroxide and a catalyst of selenium and copper. Ammonia was determined by an auto-analyser system based on colorimetric determination of ammonia transferred to indophenol blue (Dahl 1973, 1974). This method has many modifications and the one used here is, in brief: The sample is made alkaline by sodium hydroxide to be within the pH-range 10.5 to 11.8. This is followed by addition of phenol and excess of sodium hypochlorite with sodium nitroprusside (sodium pentacyanonitrosylferrate) as catalyst. Sodium citrate was also added to prevent precipitation of magnesium hydroxide. To speed up the development of indophenol blue the sample was passed through a water bath of 70°C and immediately after that the colour strength was measured at 630 mm.

For analysis of P, K, Ca, and Mg a sample of about 0.4 g was digested for about 2 days in a mixture of nitric acid and perchloric acid. During boiling the sample was not allowed to exceed 160°C. After that the dry sample was dissolved in 3 M hydrochloric acid and evaporated to dryness. This was repeated three times whereupon the sample was dissolved by 2 M hydrochloric acid and diluted with water. This solution was then divided for the different analysis.

Phosphorus was determined as "phosphomolybdenum blue" after reduction by ascorbic acid (Murphy and Riley 1958, Henriksen 1971, 1972). The analysis was performed in an auto-analyser system. The mixed reagent contained ascorbic acid, sulphuric acid, ammonium molybdate and oxalic acid. Before the measurement of "phosphomolybdenum blue" at 872 nm the sample was heated to 80°C in order to speed up the development of the colour.

In the analysis of the needles for the other nutrients, K, Ca and Mg, the measurements were made on the same acid-digested sample as for P.

An Eppendorf flame-photometer using a gasol (propane-butane)-air flame was used for total-K and a Perkin-Elmer 403 atomic-absorption-spectrophotometer was used to determine Ca and Mg (cf. Bowen 1967). Before the measurements lanthanum was added to the sample. Ca was measured at 211 nm and Mg at 285 nm.

4. Results

Samples for analyses of mineral nutrient contents in needles were taken according to Table 6. The needle samples were analysed for their contents of N, K, P, Ca and Mg. However, the capacity is insufficient for immediate analysis of all samples and some of them were given priority in order to get a rough picture of the changes in mineral nutrient content during the period of the experiment. Some of these results are discussed in this report.

From Table 6 it can be seen that samples were taken from all five blocks on 1974-09-26, 1975-09-18 and 1976-09-16. Table 7 shows the nitrogen content of the needles on these occasions in percentages of dry weight with the mean value and standard error for the five blocks. Standard error is quite small. The highest nitrogen content of the needles older than the current ones never exceeded 2%. The older the needles are the lower the content. This applies both to treated and control plots. During the autumn of 1974, however, there were not enough C+3 needles on I and O plots for samples to be taken. The nitrogen content in the autumn was almost the same in all three years with a trend towards a lower content in 1976.

Variation in nitrogen content during 1975 as a percentage of the dry weight is shown in Figure 8. The first samples of current needles were taken on 1975-06-26 when the needles were large enough for picking. The points on the line are a moving average of three values, except for the initial and final values which are discrete ones.

The different treatments influence the nitrogen content of the needles. The nitrogen content of needles from I plots is somewhat higher compared with the control and the content is still higher in IF plots. The highest values were found in needles from F plots (cf. Table 7).

Table 7. Nitrogen content as per cent of dry weight in exposed needles from whorl three 1974, 1975 and 1976. Each value is an average for five plots.

Treat-ment	Needle age	Date for needle sampling 1974-09-26	 1975-09-18	 1976-09-16
IF	C	1.65±0.06	1.73±0.03	1.52±0.05
	C+1	1.56±0.04	1.64±0.04	1.59±0.03
	C+2	1.45±0.02	1.55±0.01	1.48±0.04
	C+3	1.21±0.03	1.31±0.02	1.26±0.04
F	C	1.96±0.02	2.03±0.03	1.66±0.02
	C+1	1.91±0.04	1.93±0.03	1.80±0.04
	C+2	1.61±0.04	1.78±0.05	1.65±0.05
	C+3	1.40±0.04	1.48±0.03	1.38±0.02
I	C	1.38±0.02	1.31±0.04	1.03±0.01
	C+1	1.32±0.02	1.37±0.04	1.05±0.03
	C+2	1.25±0.01	1.27±0.01	1.08±0.03
	C+3	- -	1.11±0.03	0.98±0.04
0	C	1.29±0.03	1.23±0.01	1.11±0.03
	C+1	1.28±0.08	1.21±0.04	1.03±0.02
	C+2	1.17±0.04	1.18±0.01	1.00±0.01
	C+3	- -	1.03±0.02	0.95±0.02

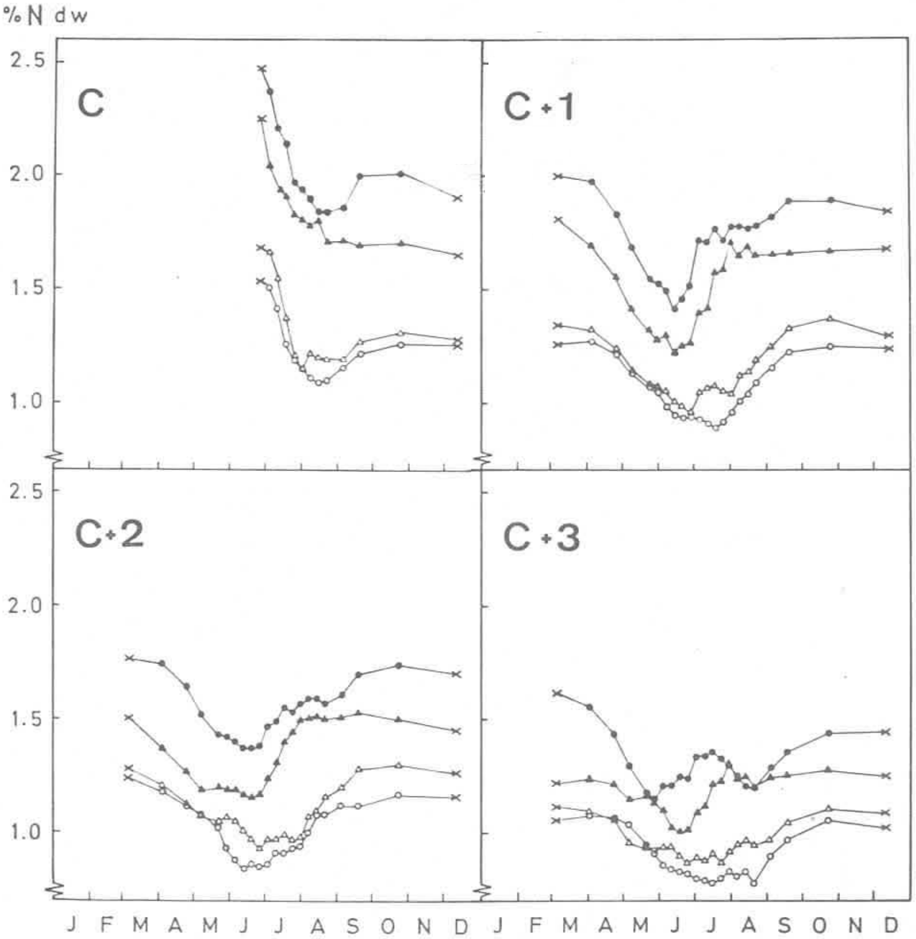

Figure 8. Nitrogen content on dry weight basis in needles from the third whorl. Moving average for three values except the initial and ending value for each line (x) which are discrete values. ○: control; △:irrigation; ●: fertilization and ▲: irrigation plus fertilization.

During the summer the nitrogen content based on dry weight first diminishes and then increases. The minimum for F and IF plots is in the second half of June, except for current needles, whereas for I and 0 plots this minimum comes about one month later.

The dry weight of the needles fluctuates during the year. When the mineral nutrient content is expressed on a dry weight basis this content expression will fluctuate as well. This variation is avoided by using nitrogen as a basis instead of dry weight for all other nutrient content expressions. It will not be possible to discuss which basis for the nutritional expressions is the most efficient for ecological evaluations until the various biomass figures are available.

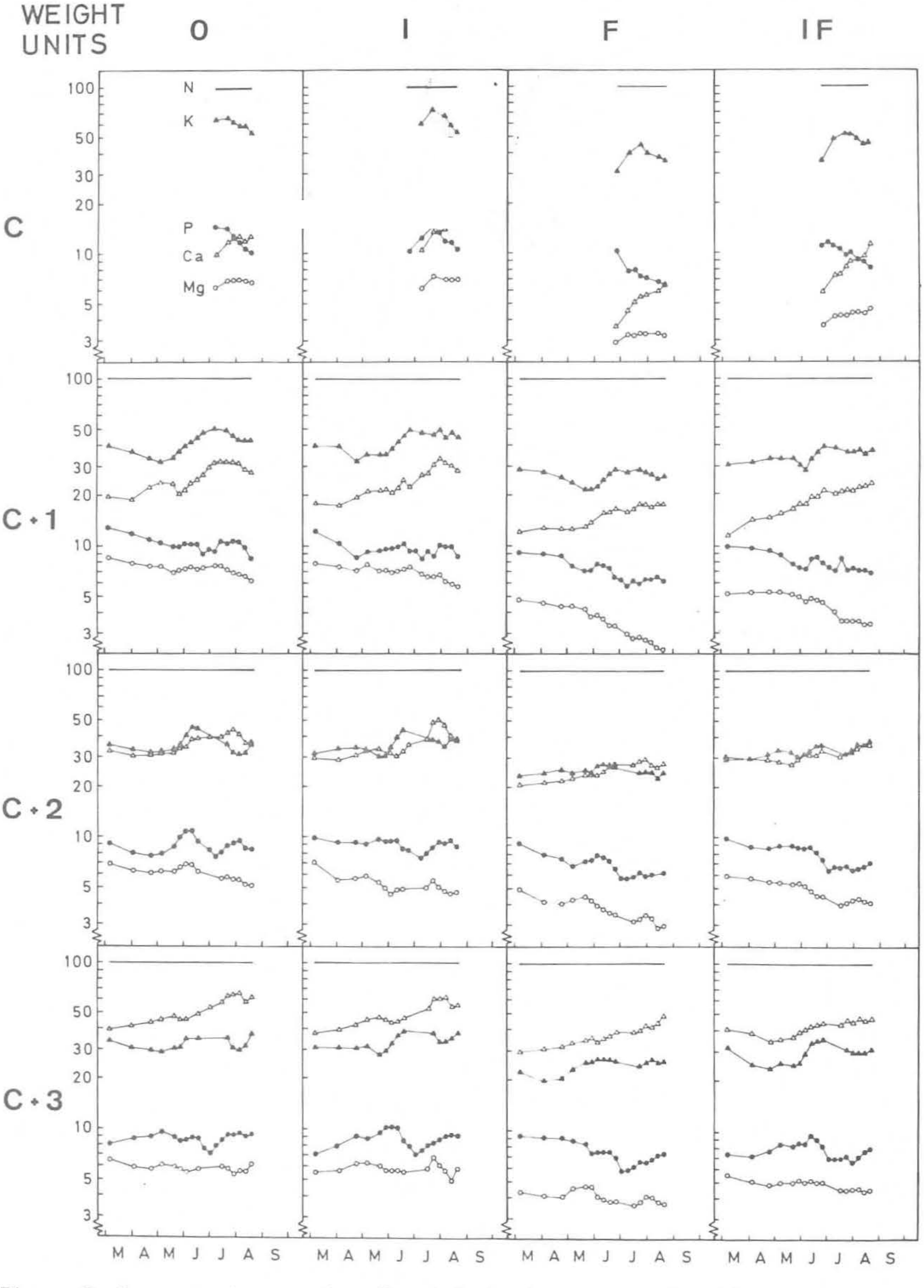

Figure 9. Content of some mineral nutrients in relation to nitrogen (100 weight units). Needles taken from the third whorl, 1975. Logarithmic scale. ——: N (=100); ▲: K; △: Ca; ●: P; ○: Mg.

Figure 9 shows the variation of the needle content of K, P, Ca and Mg during the summer months of 1975. In the figure the nitrogen content is put to 100 weight units and the other elements are put in relation to this in a logarithmic scale.

In relation to nitrogen the potassium content in current needles seems to have a maximum in the middle of the summer but the content is a little lower in F and IF plots than in 0 and I plots. The same is also more or less valid for the other needle ages. The potassium content is highest in current needles and then decreases.

The content of phosphorus diminishes during the summer for the three youngest needle ages but for C+3 needles it is more constant. This trend is equal for treated and control plots. The mean content of phophorus is almost equal in the four different treatments with a trend to be lower in F and IF plots.

The content of magnesium shows a more complicated picture as it is fairly constant during the summer in current and C+3 needles or shows a trend to increase (current needles in IF). In C+1 and C+2 needles the content diminishes with time, sometimes drastically, see C+1 in F and IF plots. Generally the magnesium content is lower in F and IF plots than in 0 and I plots.

The content of calcium increases with time at all needle ages and this increase is very pronounced in current needles in all types of treatments.

During 1975 the few plants of birch and Salix species were removed from the plots. The amount of nitrogen per m^2 thus removed from the area is shown in Table 8. The maximum amount removed was 97.8 mg and should be compared with the total amount, 17 g N, given to the IF plots during the period of treatment.

In order to study how the treatment had increased the content of ions in the soil, cores were taken from the plots in block two on two occasions in 1976 (Table 9). The first was on June 15, 12 days after the F plot had been fertilized with 8 g N/m^2. The second occasion was on August 20 when the fertilization of the IF plot with 15 g N/m^2 just had finished.

Table 8. The amount of nitrogen removed from the plots with the plants of birch and Salix species, autumn 1975.

Treatment	Plot no	Dry weight g	N-content % dw	N amount per m^2 mg
IF	4	6 212	1.89	97.8
	7	1 532	2.10	26.8
	12	765	1.98	16.8
	13	449	1.94	9.7
	20	2 430	1.27	25.7
	x	2 278	1.84	35.4
	s	2 329	0.33	35.6
F	1	1 808	1.59	24.0
	5	540	1.76	7.9
	10	1 076	1.92	23.0
	14	1 902	1.61	34.0
	19	1 864	1.14	17.7
	x	1 438	1.60	21.3
	s	606	0.29	9.5
I	3	4 802	1.37	54.8
	6	690	1.18	6.8
	11	105	1.18	1.3
	16	319	1.06	3.8
	17	1 424	1.10	13.1
	x	1 468	1.18	16.0
	s	1 930	0.12	22.2
0	2	2 176	1.12	20.3
	8	2 207	1.71	31.4
	9	350	0.92	3.6
	15	518	1.03	5.9
	18	273	1.10	2.5
	x	1 105	1.18	12.7
	s	996	0.31	12.7

Table 9. Conductivity (μS) in water extracts of 50 ml soil in 50 ml water. Samples taken from block no 2. 12 cores per plot divided into the different layers and mixed randomly four and four to three samples per plot.

Treatment	Sampling date		Layer			
			Humus	Mineral soil, depth in cm 0-10	10-20	20-30
0	76-06-15	x	83	50	37	32
		s	6	2	4	5
	76-08-20	x	84	30	19	14
		s	12	3	4	4
I	76-06-15	x	72	49	49	40
		s	23	13	12	5
	76-08-20	x	48	33	20	16
		s	10	3	1	3
F	76-06-15	x	287	96	68	54
		s	91	37	14	2
	76-08-20	x	98	70	41	44
		s	30	20	17	14
IF	76-06-15	x	92	75	46	39
		s	2	21	14	9
	76-08-20	x	84	65	45	37
		s	12	10	11	7

Twelve cores per plot were taken down to a depth of 30 cm in the mineral soil. The cores were then divided into four parts, one from the humus layer and three from the mineral soil. From four cores each of the four parts were mixed together, thus giving four times three samples from each plot for the analyses. An amount of water corresponding to the volume of the soil sample was added. The samples were shaken and allowed to stand overnight before the conductivity was measured. The highest conductivity was found in the F plot on June 15, 12 days after fertilization. At 20-30 cm below surface on the 0 plot the conductivity was 32 ± 5 and the corresponding value for the IF plot was 39 ± 9, which indicates a slight increase in the content of ions in the soil due to percolation of mineral nutrients.

The concentration of single ions was determined by L. Bringmark from soil samples at 20-30 cm below the surface (Table 10). Rather high concentrations were found on IF plots in comparison with 0 plots. The samples were

Table 10. Concentrations of some ions in water extracts, µmol/l. 100 g moist soil extracted by 150 ml water. The samples taken from a depth of 20-30 cm below the surface on the 18 June 1976. Samples were taken from blocks 1-4 with three subsamples per plot. The study was performed by L. Bringmark.

Treatment	Concentration of ions in water extracts, µmol/l							
		H^+	NH^+_4	NO^-_3	K^+	Ca^{2+}	Mg^{2+}	Na^+
0	x	10	5	3.1	14	11	9	26
	s	4	3	1.8	8	6	4	8
I	x	9	4	1.4	15	9	5	39
	s	7	2	1.3	9	6	4	9
F	x	20	44	55	69	38	24	35
	s	15	85	111	59	41	26	13
IF	x	16	15	52	103	27	23	55
	s	5	8	40	54	15	14	21

t-test, the probability for differences between the mean values, x 95%, xx 99%.

	H^+	NH^+_4	NO^-_3	K^+	Ca^{2+}	Mg^{2+}	Na^+
0 / I			x				x
0 / F	x			xx	x	x	
0 / IF	xx	xx	xx	xx	xx	xx	xx
I / F	x			xx	x	x	
I / IF	x	xx	xx	xx	xx	xx	x
F / IF							x

taken on 1976-06-18 just after a heavy rain of about 17 mm which might have caused percolation, see Figure 11.

5. Discussion

The irrigation technique used with sprinklers at a height of about 50 cm and an average spacing of about 5 m (Figure 7) has two disadvantages: the irrigation will not be completely even and the ground flora will be moistened by the irrigation water. If the water was distributed above crown level, the spread would be fairly even, but then even the tree crowns would be affected by the irrigation water, and wind drift to neighbouring plots would cause further disturbances. A drip system could theoretically distribute water and fertilizer quite evenly and with negligible wetting effects, but this is difficult to achieve in practice in the field and would imply laborious control and maintenance routines. However, the unevenness in distribution may be regarded as insignificant for the trees because of wide and even root distribution on the plots. The wetting of the ground flora may either effect the water turn-over of the plants and/or the mineral nutrient leaching out of the leaves. The former effect may be regarded as temporary and the second as already mentioned, does not affect the tree needles.

The irrigation was carried out during the night or in the early morning in order to minimize the evaporation losses of water supplied. At this time wind drift is at a minimum, but on the other hand the dripping off from the vegetation will be delayed.

During three years of experience of the irrigation system no visible effects have been noticed of uneven distribution or of wetting the ground flora on, for instance, growth of the trees or other plants.

As mentioned in section 3.1, the soil water status was better in block 1 than in blocks 2, 3 and 4 when the experiments started. Block 5 was intermediate. This inhomogeneity within the experimental area has also been shown by measurements of water potentials of the pine needles (Hellkvist et al. 1975). Furthermore, the first visual effects of the treatments were observed on the IF plot in block 1, indicating a higher reaction ability of the ecosystem here. The mosses and *Vaccinium* species started to grow rapidly and the pine needles turned dark green. Measurements made by S. Linder showed an increased chlorophyll content in the needles. During 1975 a much stronger effect was observed (Figure 10).

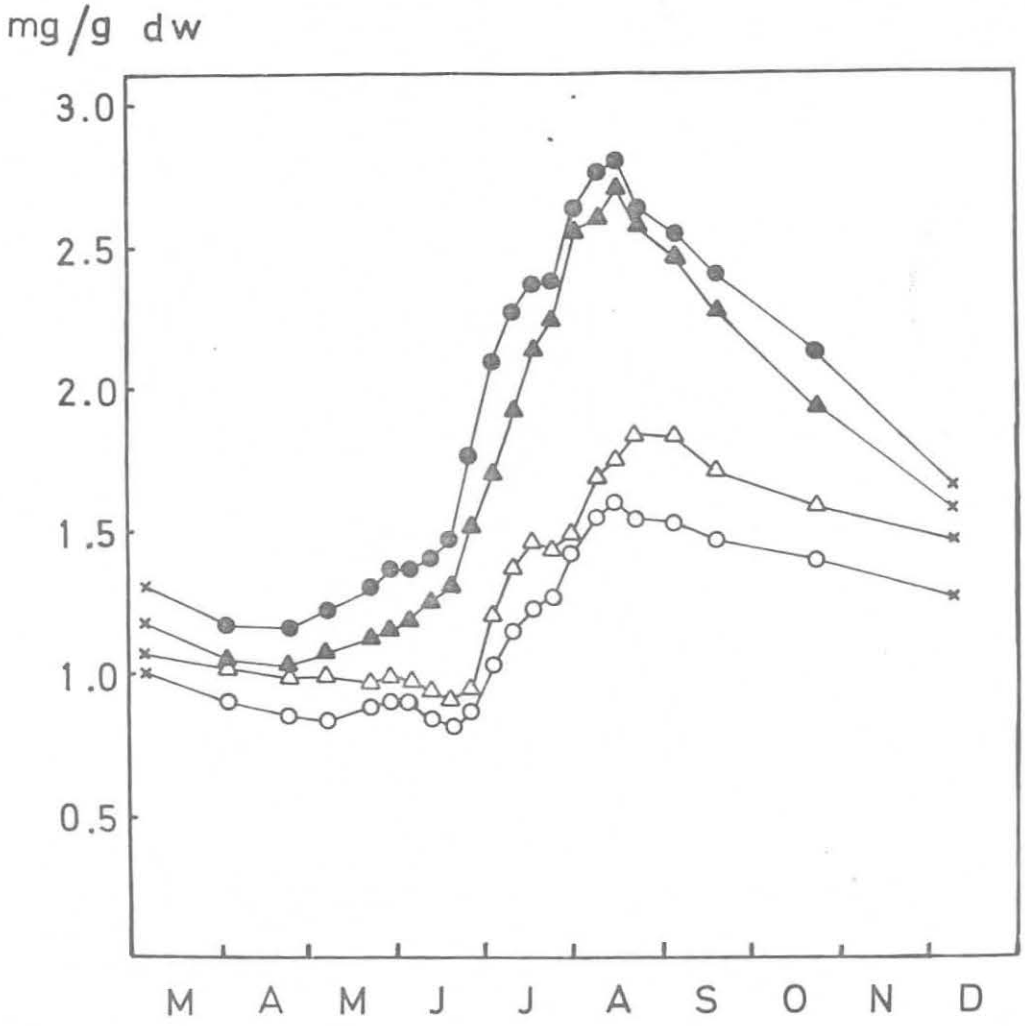

Figure 10. Variation in chlorophyll content during 1975. C+1 needles taken from the third whorl. Moving average for three values except the initial and ending value for each line (x) which are discrete values. ○: control; △: irrigation; ●: fertilization; ▲: irrigation plus fertilization. (Data from S. Linder).

The soil water potential, Ψ_S, has been measured by P-E. Jansson on plots with different treatments. Some results from one of the control plots are given in Figure 11, where it is seen that Ψ_S varies strongly with precipitation at a depth of 15 cm and pronounced effects are also seen at 30 cm. At deeper depths Ψ_S is more or less constant, about -50 mbar, but may be influenced by heavy rain even at very deep depths. The results from an IF plot show another picture for the shallow levels, and it seems that the water status in the ground is no longer a growth limiting factor. However, on these plots heavy rains also affect Ψ_S at deep depths.

The percolation of water through the ground may cause a transport of mineral nutrients downwards. Table 10 shown soil contents determined by L. Bringmark on samples taken on 18 June 1976. The samples were taken after 17 mm rainfall and indicate a considerable transport in both F and IF plots.

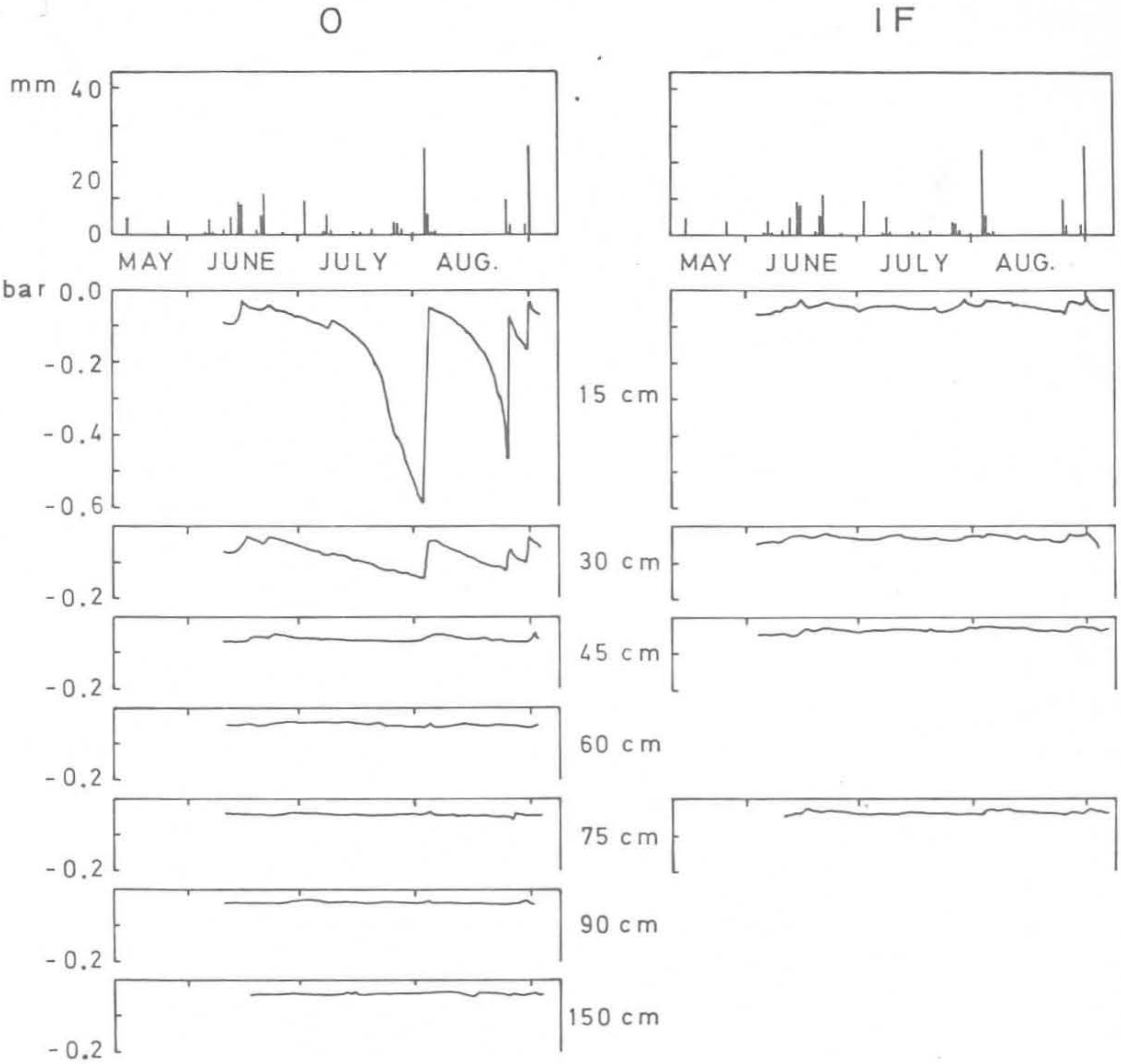

Figure 11. Precipitation, mm (on top) and soil water potential, bar (at the bottom) at different depths below the surface on O and IF plots (no 18 and 20) during the summer 1976. Soil water potential measured by tensiometers and performed by P-E. Jansson.

The sampling was carried out four weeks after the start of liquid fertilizer additions and two weeks after the application of solid fertilizer. Measurements of the conductivity in water extracts from different soil layers on June 15 and August 20 the same year (Table 9) show that in the humus layer an increased salt level is only noticeable in the F plots treated with solid fertilizer and on the first sampling occasion. A similar tendency is found deeper in the soil, but here an increased salt level remains on the later occasion in both these plots and the IF plots. More data are required before these relationships can be understood and this factor will be studied more intensively in 1977.

The aim of the irrigation and fertilization experiment is to reduce or, if possible, to abolish the water and the mineral nutrient availability as growth limiting factors and to study the behaviour of the ecosystem, especially the pine tree reactions. This aim implies a physiological status in the trees which changes from a stress level of both factors to an optimum situation which in turn means trees with completely different properties to those at the start of the experiment. These properties are unknown and therefore at our present stage of knowledge we are unable to determine when we have achieved our objectives. However, the change may be expected to take several years, especially since the whole ecosystem has a high buffering capacity against changes. At present the aims must be restricted to following the changes and to gathering as much information as possible about the reactions of the ecosystem. No clear conclusions can be drawn here because the stand is in a process of fast alteration and many of the samples are still being analysed.

The composition of the fertilizer added in the IF treatment is in agreement with the nutrient requirements of birch seedligs (Ingestad 1971, Table 5). This composition means a rather high addition rate of K, Ca and Mg in relation to the requirements of pine seedlings (Ingestad 1977a) but the deviation is strongly motivated by the fact that not only the pine trees are to be fertilized but also other plants which may have other requirements, and also that the higher levels of the cations may not be expected to hamper the pines since the deviation is small.

The visible reaction to the treatment in the IF plots has been dramatic as both ground vegetation and trees have changed in colour and growth. Even the lichens reacted with a strong growth increase (Figure 12). This dramatic change is not seen in the I or in the F plots. It would thus appear probable that both the water and the mineral nutrition factors are of great importance to the ecosystem. However, it must be remembered that the fertilization in the IF and F plots is different in two ways: The fertilizer applied in the IF plots is complete also with regard to the micronutrients and the fertilizer is applied in small dosages in contrast to the once-a-year application of the solid fertilizers. Thus, the differences in reactions between the fertilization

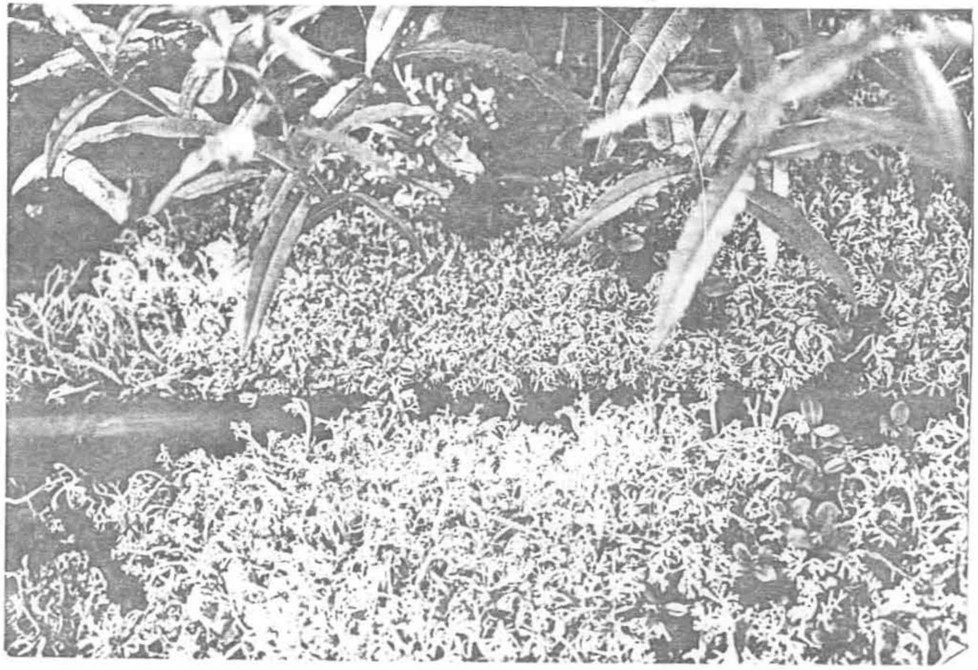

Figure 12. Photo taken in the autumn 1975 showing a Cladonia species growing over an irrigation tube.

treatments cannot entirely be referred to the difference in water regimes. The pure salt effects of single and high fertilizer applications in the traditional technique are, however, amplified by periodical lack of water in the soil and this effect is diminished or absent in the IF treatment. This difference seems to be one of the major causes of the drastic difference in ground flora reactions between the two treatments: Whereas a rich and fast-growing ground flora is developed on the IF plots the fertilization of the F plots has a marginal effect on these plants. The nitrogen contents have increased considerably in the needles in both types of fertilization treatment (Table 7, Figure 8). This effect was obvious at all needle ages and already in the first season. The effect is most pronounced in the F plots throughout. A similar tendency was seen in 1974 and 1975 in the I plots, but this faded out in 1976, indicating that an increased water regime in the soil may increase the mineralization rate of nitrogen but that increased growth "dilutes" the increased nitrogen content by insufficient access to nitrogen in the long run and that nitrogen remains a growth-limiting factor just as before. This "dilution" process is still more pronounced in the IF treatment, since the contents of nitrogen, despite increased application rates (Figure 5, Table 2), are not kept at a constant level but decrease in 1976. The increase in growth rate of the total biomass may have exceeded the increase in fertilization rate. However, the increase in the amount of needles in the pine crowns makes it probable that increasing shading at the ground level will diminish the mineral nutrient consumption rate of the ground flora and eventually increase the turnover rate and, therefore, a further increase in the fertilization rate is not planned.

An optimum nitrogen content in the needles may be estimated to about 1.7-2.5% N of the dry weight under the prerequisite that all other nutrients occur in an optimum relation to nitrogen (Ingestad 1977b). Similar levels have also been reported by Tamm (1977) and this is confirmed in the F plots where this level of nitrogen is present most of the time in the C-needles (Figure 8, Table 7). In the IF plots this level is reached only temporarily. It is probable that the applied nitrogen in the IF plots is much more efficiently utilized by the vegetation than in the F plots because of the slow dosage procedure in the former treatment, even if the total nitrogen amount supplied is higher (Table 2). It is, therefore, to be expected that the biomass production is very much increased by the irrigation and by the dosage technique in the IF treatments, leading to more pronounced "dilution" effects. The continued treatments will show whether a more optimal internal nutrient status occurs in the pines also in this treatment and evaluation of the growth measurement data will reveal the fertilizer efficiency of the various treatments.

Pine seedlings at optimum nutrition contain the mineral nutrients in the following weight proportions: 100 N: 50 K: 13 P: 6 Ca: 6 Mg (Ingestad 1977b). The relative levels found in the needles from the different treatments during 1975 of K, P, Ca, and Mg are given in Figure 9 (nitrogen put equal to 100). It is seen that in the 0 and I plots the nutrient proportions mentioned above are largely present in the current needles. P decreases to rather low values at the end of the season and Ca is fairly high and increases continuously with increasing needle age. In the F treatment there is a general tendency that all nutrient levels in relation to nitrogen are depressed, no doubt as a result of a "dilution" effect by increased growth rate. The same tendency is seen in IF treatment, but is generally not so pronounced, probably because the addition of a complete fertilizer is important for obtaining optimum nutrient proportions also under field conditions. However, so far the levels of P, Mg, and possibly K in older needles do not seem to have remained in an optimum relation to nitrogen, neither in the IF nor in the F treatments. Furthermore, the Ca contents are high in relation to the required level and this may strengthen the deviation from the optimum proportions of K and Mg by ion antagonism. It is not known at present to what extent such factors affect growth and health in natural stands of pine, but there are several reasons for the stand being still far from the status of non-limiting nutrient conditions aimed at in the IF treatment.

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